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"COST EFFECTIVENESS: INCENTIVE STIMULANT
FOR FUTURE SPACECRAFT PROGRAMS"

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INTRODUCTION

In an ORSA publication outlining the content of Operations Research the following two sentences can be found: "It frequently happens today, that complicated systems involving men and machines operating under accepted groundrules in a natural environment exhibit stable aspects in their behavior," "Operations Research is the science that is devoted to describing, understanding, and predicting the behavior of such man-machine systems operating in natural environments;..."

The thesis of the following paper is that even in systems which exhibit marked irregularities and instabilities and about which there is considerable uncertainty and for which groundrules are frequently changed, operations research techniques can contribute in a fruitful way to effective operations. In the management of such systems decisions effecting operations are made based on either the intuition of decision makers or on the combination of precise logical analysis and that same intuition. It is reasonable to suppose the latter is preferred.

The Apollo Manned Lunar Landing Program has extended manned spacecraft technologies far beyond the limits of the Mercury and Gemini Programs. The sophisticated subsystems that comprise the manned spacecraft and the launch vehicles of the Apollo Program will serve as a technological plateau upon which economical manned spacecraft programs can be based.

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With the advent of such subsystem development and technology many space missions become feasible. A prime problem facing space program managers today is: "How is it possible to take maximum economic advantage of the technical accomplishments of the Apollo program in the planning of future space programs?"

The cost-effectiveness techniques used in the Department of Defense have provided methods of determining which of proposed future programs or concepts is both economical and most in accord with national defense objectives. There is no reason why such techniques cannot serve the space programs of this country in the same way. There are difficulties to be sure; but they are the same difficulties that confront every use of operations research techniques.

INTRODUCTION OF AN EXAMPLE

A relatively primitive example of how cost effectiveness analysis can provide a stimulus to NASA future planning activities is in the area of manned earth orbital experimentation. Considerable discussion within the space sciences community has provoked differences in the design of the manned spacecraft systems to be used as an orbital laboratory complex in the post-Apollo years. The USAF's Manned Orbital Laboratory (MOL) now under design consists of a two man laboratory and utilizes a two man Gemini vehicle for crew rotation and resupply.

Included in NASA's plans for post-Apollo Programs is an experimental program which is to utilize Apollo Systems and modified Apollo Systems in both earth orbital experimentation and lunar orbit experimentation and survey. As such, it begins with Apollo three-man 14 days systems and extends by modifications to three-man 45 day systems. In this program each logistics vehicle has an associated laboratory; and, each launch is essentially operationally indepen dent of every other launch. The Manned Orbital Research Laboratory (MORL) under study by Langley Research Center is conceived as a six man laboratory utilizing a modified three man Apollo vehicle for crew rotation and resupply. Various studies of other concepts ranging up to a thirty-six man laboratory and a twelve-man logistic vehicle have been conducted. Such concepts have been found to be initially feasible utilizing only launch vehicles either already developed or under development in the Saturn series. As one might expect both the nonrecurring development cost and the recurring cost per unit of a larger orbital laboratory are greater than the corresponding costs of a smaller orbital laboratory. However, this larger laboratory provides greater resources per laboratory unit for the conduct of experiments in orbit when compared with the smaller laboratory module. It is reasonable then to compare the costs of alternative systems in terms of the resources which they provide.

THE ANALYSIS AND RESULTS

A detailed study was undertaken by the Manned Spacecraft Center to investigate the advantages and disadvantages of the various proposed concepts for earth orbital experimentation. Part of the result of this investigation was concerned with a gross-level analysis of the effect of the major system parameters of the concepts on the cost-effectiveness of the total program. It is beyond the scope of this paper to delve into the details of this study. It suffices to outline the major steps taken and the major conclusions reached.

In the analysis that was made of this subject the effectiveness measure chosen was an estimation of the number of useful productive experimental manhours produced by a laboratory concept as a function of the crew size of the laboratory module itself. The non-recurring developmental cost is essentially an initial cost, producing no manhours of orbital experimentation. For a given concept an increase in the time of orbital operations of the laboratory produces a corresponding increase in the effectiveness measure of useful orbital manhours. The same increase in time incurs an increase in cost over the initial non-recurring cost by the launching of logistics vehicles and the placement of laboratory modules in orbit.

The parameters under study involved more than merely crew sizes. Concepts are under study which require the logistics vehicle to provide to the laboratory most of the subsystem support needed for the experimental operations. Other concepts would utilize a laboratory with full subsystem support capabilities which would require only resupply of expendables from the logistics vehicles. The former type of laboratory is called "dependent" and the latter "independent" for identification purposes. Further, some concepts provide systems and require crewmen to operate continually in space for 90 days (or even as long as six months in some of the larger systems concepts). The time allowed between crew changes is a factor which cannot be determined on a basis of cost alone since the effects of prolonged activity in a zero gravity condition are not fully known. In fact, without exception, the larger systems concepts provide at least partial gravity either through use of onboard centrifuges or through the spinning of the entire laboratory. Early post-Apollo programs are assumed to require less than ten-man crews in the laboratory and up to 90 days crew duty cycle for each crewman. The results of this analysis can be seen on the graphs of cost versus effectiveness for the twenty-four concepts studied as alternatives to the use of unmodified Apollo systems.

For relatively small sized missions of 12,500 manhours, larger crew sizes for both the laboratory and the logistics vehicle are indicated. Further, increases in the duty cycle are clearly warranted and the upper limit is to be determined by factors other than cost. An interesting fact that seemingly has been overlooked in past studies is that greater savings are possible through increases in the logistics vehicle crew size than by corresponding increases in the laboratory crew size. Dependent laboratories offer savings over independent laboratories for small crew sizes and small mission size; but, as crew sizes or mission size increase the advantage of dependent laboratory systems either becomes insignificant or becomes a cost disadvantage.

A NEW FACTOR

Because of the large nonrecurring costs involved for some of the conepts the tendency in planning has been to utilize existing hardware and develop a minimal system as the first step and then, in the second step, develop an improved system. Such has been the suggestion with the MORL; develop the six man laboratory using a three man modified Apollo for logistics resupply for the first phase; and, then develop a six man logistics vehicle to provide the added efficiency that such a development would bring. This appears to be both logical and reasonable. However, this analysis indicates that there is a significant alternative worthy of further study. Since greater cost reduction accompanies increased logistics crew size when compared to increased laboratory size, it would be desirable to take advantage of this increased efficiency as soon as possible in the accomplishment of the total mission. It may seem incredible that a six or even nine man logistics vehicle and a three man laboratory module are in any way compatible. However, several of the more efficient and less costly three man laboratory designs incorporate the ability to dock with one or more copies of themselves to form a larger space laboratory. Thus an alternative to the MORL approach is suggested. This alternative is likewise in two phases: (1) the first phase consists of the development and utilization of a large six man logistics vehicle and small dependent three man laboratories docked in series; (2) the second phase consists of the development and utilization of a larger single six man laboratory and the utilization of the logistics vehicle of the first phase.

This concept avoids the concurrent large development costs of both a six-man laboratory and a six man logistics vehicle, as does the MORL approach, and also avoids the high recurring costs of the small three man logistics vehicle servicing a large six man laboratory. This alternative concept offers several important advantages. For example, the six man logistics vehicle initially developed could continue to be used as a logistics vehicle to service the larger space stations of the future. In addition, the laboratory module developed in the second phase could serve as a basis for the development of an efficient Mars or Venus mission module if such a mission were desired.

The comparison on the basis of the study of the Cost-to-Effectiveness relationship for earth orbital operations only indicates for a medium mission size of approximately 37 thousand manhours of experimentation, a dollar saving of about 750 million dollars is possible utilizing this concept instead of the MORL approach. Clearly this is a significant factor. While this concept has been analyzed only on a gross level, it is seen that by employment of a cost-effectiveness analysis, a concept that heretofore has been ignored, is now indicated to be quite promising.

PROBLEMS OF ANALYSIS

1. Cost Estimation

In cost effectiveness analysis, the necessity for adequate cost estimation is obvious. The problem of estimating the cost of space vehicles is probably as great as in any other field. Not only is there variation in reporting actual costs incurred, but there is variation in design and fabrication of the space vehicles themselves. This is to be expected since the types of vehicle subsystems and components differ with different programs and also change rapidly as advancements in the state-of-the-art are made.

Synthetic models based on actual costs of past and current programs must therefore be constructed. Gross-level cost estimating relationships can be derived for use in cost estimation even when only meager information is available. Considerable care is required in the generation of a cost model since (1) too little data is available for adequate statistical analysis of costs, and (2) routine statistical techniques can give rise to completely extraneous results if not tempered by judgment. For an example of such an extraneous result consider the following.

The nonrecurring development cost C_n of the Mercury, Gemini and Apollo programs is approximated by the empirical formula

$$\log C_n = 0.24736 \ (X - 1954.26)$$

where X is the calendar-year date of the first launch. The first item recurring cost per unit for fabrication acceptance, testing and launch support, C_r, is similarly approximated by

$$\log C_r = 0.17506 \ (X - 1958.67)$$

where X is, as before, the year of the first launch.

For an imaginary program whose first launch is to be 1980 these relationships predict a nonrecurring development cost of 2,300 billions of dollars and a first item recurring cost of nearly 5,500 million dollars. Clearly these costs exceed reasonable expectations. Further the development cost and first-item recurring cost of a program are dependent on factors other than the date of the first launch. The data used are indeed too rare to use only synthetic techniques to develop cost relationships. Considerable judgment is required to determine which parameters of systems and subsystems are those that are most cost-related. Even then, care must be used to determine the form of the relationship. Synthetic techniques can then be used to determine the parameters of that determined form for the best fit to the data.

At the Manned Spacecraft Center, we have derived models to estimate the costs of any of the 12 interrelated subsystems of a manned space vehicle. The costs, recurring and nonrecurring, are estimated based on one or more subsystem parameters, the value of which in some way reflects the associated cost. The model estimates can then be used as a starting point from which judgment and engineering intuition contribute logical deviation. The costs thus estimated should be more accurate than those estimated by judgment alone. Aside from accuracy, the consistency in the relative values of estimates for alternative concepts is significant to processes which must determine which concept is "best."

2. Spreading Cost - Funding Levels

Total costs are not the only concern when considering the cost impact of a proposed space flight program. Funding levels must be considered for any future programs. In order to effectively evaluate funding requirements for proposed concepts, we at the Manned Spacecraft Center are developing a cost rate estimating procedure based on the incomplete Beta distribution function. This function will be referred to later. Each element of cost has associated with it a spending rate function which can be predicted with some credibility using the Beta distribution. Further, since it is only a two parameter distribution it is easy to use for multiple cost elements.

3. Time Estimation

The cost rate is indeterminable if only the costs and distribution function are estimated. The calendar time for the accomplishment of the costed element and the associated consumption of funds must be estimated, as well. There is a model even for this. Similar to the cost model, a time estimation model allows systematic estimation for developmental effort on a subsystems level of proposed program. Each of the three models, Cost, Beta Cost Rate, and Time Estimation are in various stages of development and are, at present, assumed to be independent. None is ever considered complete and as current information tends to show inadequacies in the models, they are modified. The cost model has received by far the most attention, due to the controversial nature of costing.

4. Analysis or Synthesis

It should be mentioned that each of these models is based on the marriage of analytical and synthetic techniques. Rules of expediency dictate that when analysis becomes unwieldy due to uncertainty and the multiplicity of variables, synthetic techniques can provide useful results. And when synthetic techniques produce results which seem unreasonable or contrary to expectations, further detailed analysis can uncover the reasons for the apparent inconsistency.

A case in point is in the use of "least squares" fitting procedures or multilinear regression analysis. Even when data is rare, such techniques often produce adequate estimation relationships. When the two parameters of the Beta probability density function are desired from a sample, regression analysis can produce results. The problem can be outlined simply: Find the "best" estimates of a and b so that the data $\{ (X, Y)_n \}$ can be represented by $y = B' (a, b; X) =$

$$\frac{\Gamma(a + b)}{\Gamma(a) + \Gamma(b)} X^{a - 1}(1 - X)^{b - 1}$$

If the form $\log y = A + B \log X + C \log (1-X)$ were used for a "least squares" fit to the data, estimates for a ($a \doteq 1 + B$) and b ($b \doteq 1 + C$) are obtained. The "error" which is minimized is the sum of the square of the logorithms of the ratios of actual data to calculated data using three degrees of freedom represented by the three constants in the regression equation. However, only two degrees of freedom are theoretically required to estimate a and b. It is certainly not always true that $\log \left(\frac{\Gamma (a + b)}{\Gamma (a) \ \Gamma (b)} \right)$ is equal to A in every case for the a and b estimates produced by regression analysis. Further, the estimate may not be "best" because the "error" minimized by the regression is not the "error" desired to be minimized. (Minimizing the sum of the squares of the logarithm of the ratio of actual to calculated is not necessarily desired.)

In order to alleviate these conditions, an error minimization model can be used to find local minima in error functions for arbitrary functions to be "best-fitted." These local minima are, except in unusual cases, actual absolute minima; and the evaluations thus made are indeed the "best," however "best " is defined.

5. Error Effects on Conclusions

With each of these estimation procedures there is an associated error of projection. This error is certainly of real importance. However, what is also important is: "Are the conclusions based on the analyses using these techniques for estimation signficantly more accurate than the conclusions one would reach without these techniques?" In areas as inter-related and complex as those associated with space programs, it is apparent that the answer is affirmative. We cannot tolerate a negative answer.

CONCLUSION

Cost Effectiveness techniques are not new. The techniques and problems discussed in this paper are certainly not novel to those familiar with the use of cost effectiveness analysis for aiding decision-making. What is new is the growing emphasis in space program planning on the use of such techniques to eliminate uneconomical methods of mission accomplishment by applying these techniques at the program level.

Even in the relative uncertainty and instability of planning for future manned space flight programs, the logic of cost effectiveness analysis can and will contribute significantly to economical spacecraft operations.

DESCRIPTION OF FIGURES

Figure 1.

3 man logistics vehicles- 3 man laboratories

Concepts listed in order of increasing cost at 50 thousand manhours:

a. 90 day crew recycle, independent laboratory
b. 90 day crew recycle, dependent laboratory
c. 45 day crew recycle, dependent laboratory
d. 45 day crew recycle, independent laboratory

Figure 2.

3 man logistics vehicles - 6 man laboratories

Concepts listed in order of increasing cost at 20 thousand manhours:

a. 90 day crew recycle, dependent laboratory
b. 90 day crew recycle, independent laboratory
c. 45 day crew recycle, depedent laboratory
d. 45 day crew recycle, independent laboratory

Figure 3.

3 man logistics vehicles - 9 man laboratories

Concepts listed in order of increasing cost at 50 thousand manhours:

a. 90 day crew recycle, dependent laboratory
b. 90 day crew recycle, independent laboratory
c. 45 day crew recycle, dependent laboratory
d. 45 day crew recycle, independent laboratory

Figure 4.

6 man logistics vehicles - 6 man laboratories

Concepts listed in order of increasing cost at 50 thousand manhours:

a. 90 day crew recycle, independent laboratory
b. 90 day crew recycle, dependent laboratory
c. 45 day crew recycle, independent laboratory
d. 45 day crew recycle, dependent laboratory

Figure 5.

6 man logistics vehicles - 9 man laboratories

Concepts listed in order of increasing cost at 20 thousand manhours:

a. 90 day crew recycle, independent laboratory
b. 90 day crew recycle, dependent laboratory
c. 45 day crew recycle, independent laboratory
d. 45 day crew recycle, dependent laboratory

Description of Figures (Cont'd)

Figure 6.

9 man logistics vehicles - 9 man laboratories

Concepts listed in order of increasing cost at 5 thousand manhours:

a. 45 day crew recycle, dependent laboratory
b. 45 day crew recycle, indepedent laboratory
c. 90 day crew recycle, dependent laboratory
d. 90 day crew recycle, independent laboratory

Figure 7.

3 man logistics vehicle with 3 man laboratory for 14 day recycle period (Apollo hardware). This was not considered as an alternative but is presented for reference. All non-recurring costs are assumed to be attributed to the Lunar Landing Program.

Figure 8.

3 man logistics vehicle, 45 day crew recycle, independent laboratories

Concepts listed in order of increasing cost at 50 thousand manhours:

a. 3 man laboratory
b. 6 man laboratory
c. 9 man laboratory

Figure 9.

9 man laboratories, 45 day crew recycle, independent laboratories

Concepts listed in order of increasing cost at 50 thousand manhours:

a. 3 man logistics vehicle
b. 6 man logistics vehicle
c. 9 man logistics vehicle

Figure 10.

Independent laboratories, 45 day crew recycle.

Concepts are listed in order of increasing cost at 50 thousand manhours:

a. 6 man logistics vehicle, 6 man laboratory
b. 3 man logistics vehicle, 6 man laboratory
c. 3 man logistics vehicle, 3 man laboratory

Description of Figures (Cont'd)

Figure 11.

Independent laboratories, 90 day crew recycle

Concepts listed in order of increasing cost at 50 thousand manhours:

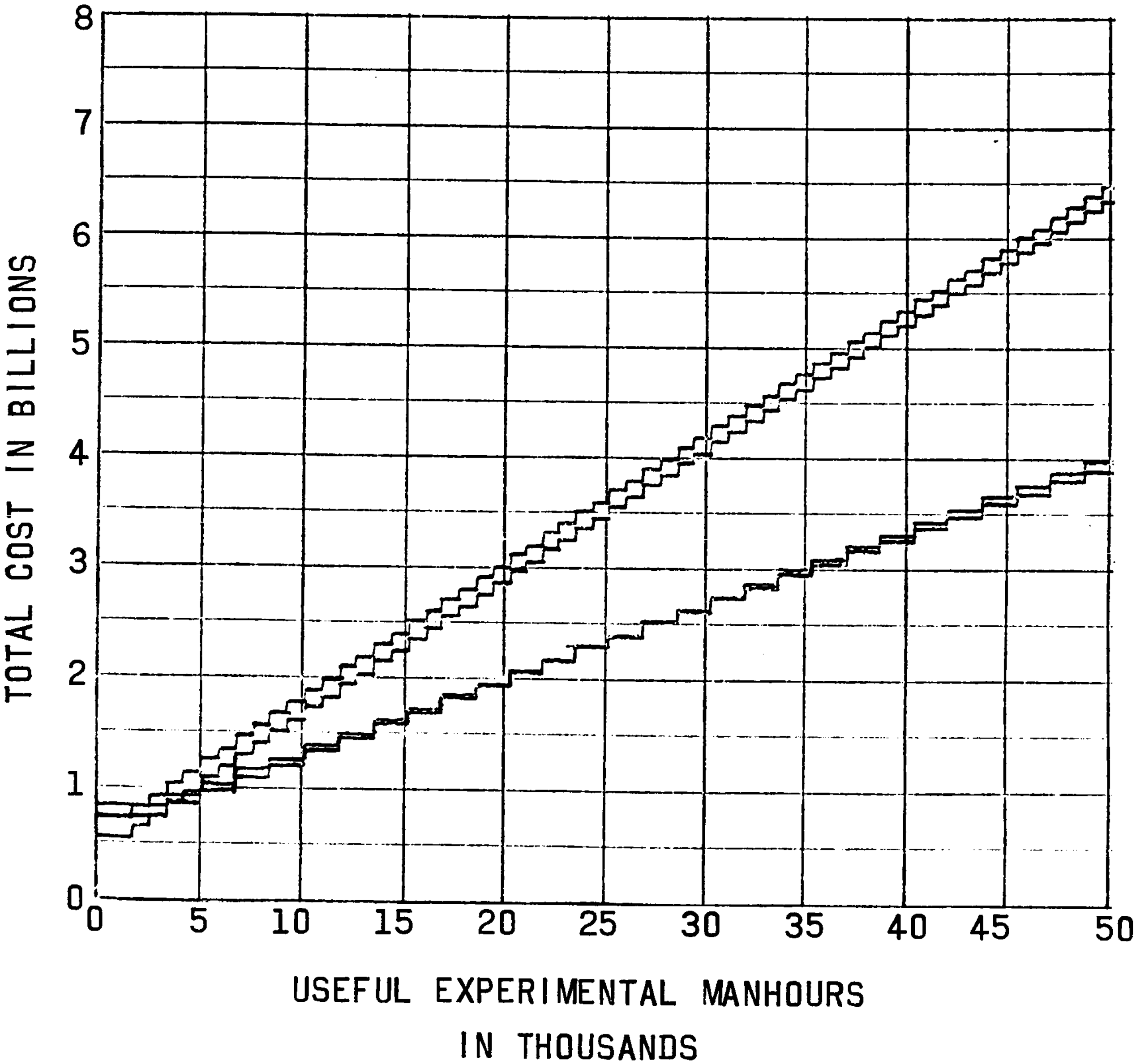
a. 6 man logistics vehicle, 6 man laboratory
b. 3 man logistics vehicle, 6 man laboratory
c. 3 man logistics vehicle, 3 man laboratory

Figure 12.

Concepts listed in order of increasing cost at 2 years (for 6 man laboratories):

a. Alternative concept
b. MORL suggested concept

ALTERNATIVES FOR EARTH ORBITAL LABORATORY COMPLEX



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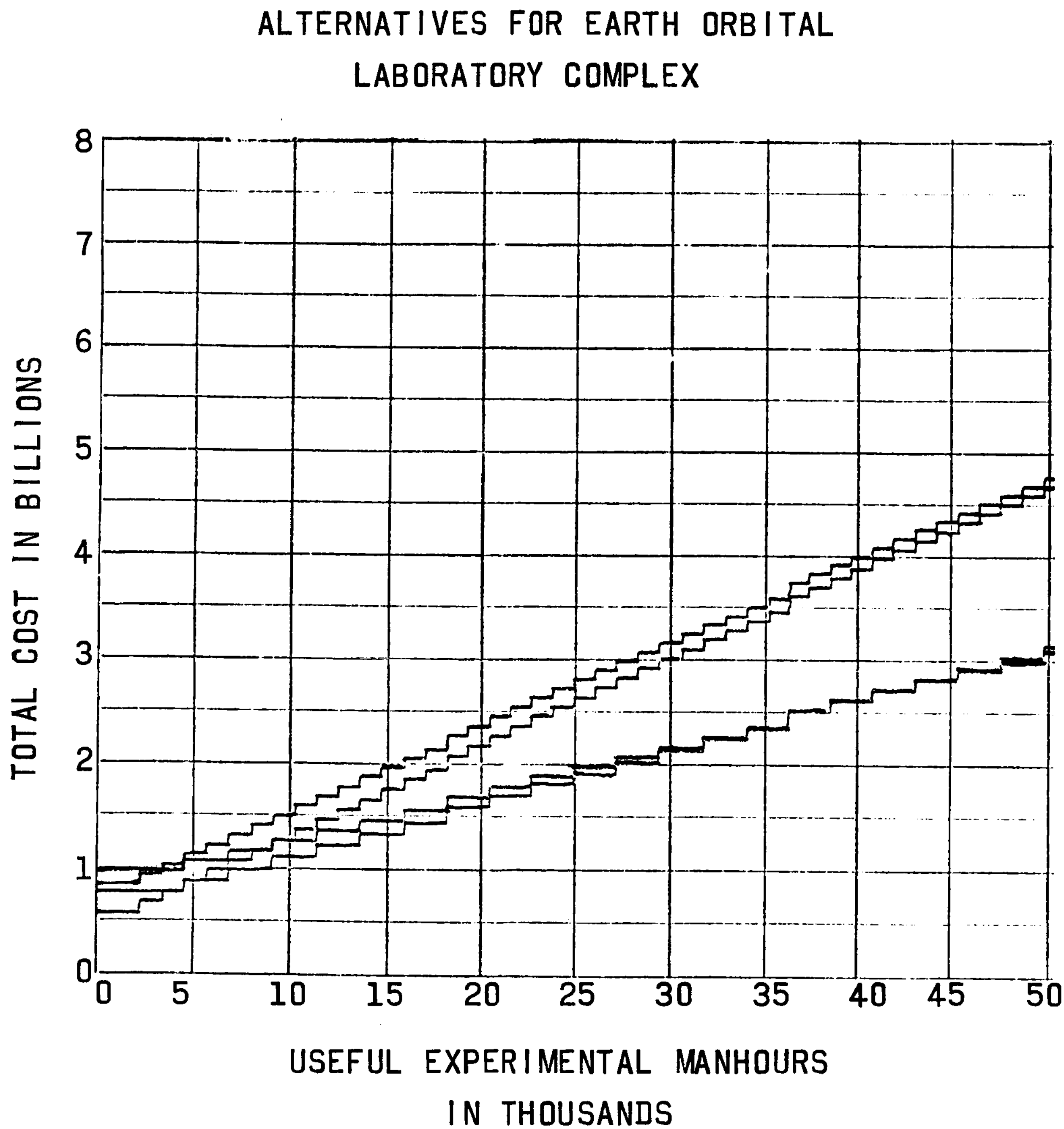
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Figure 2

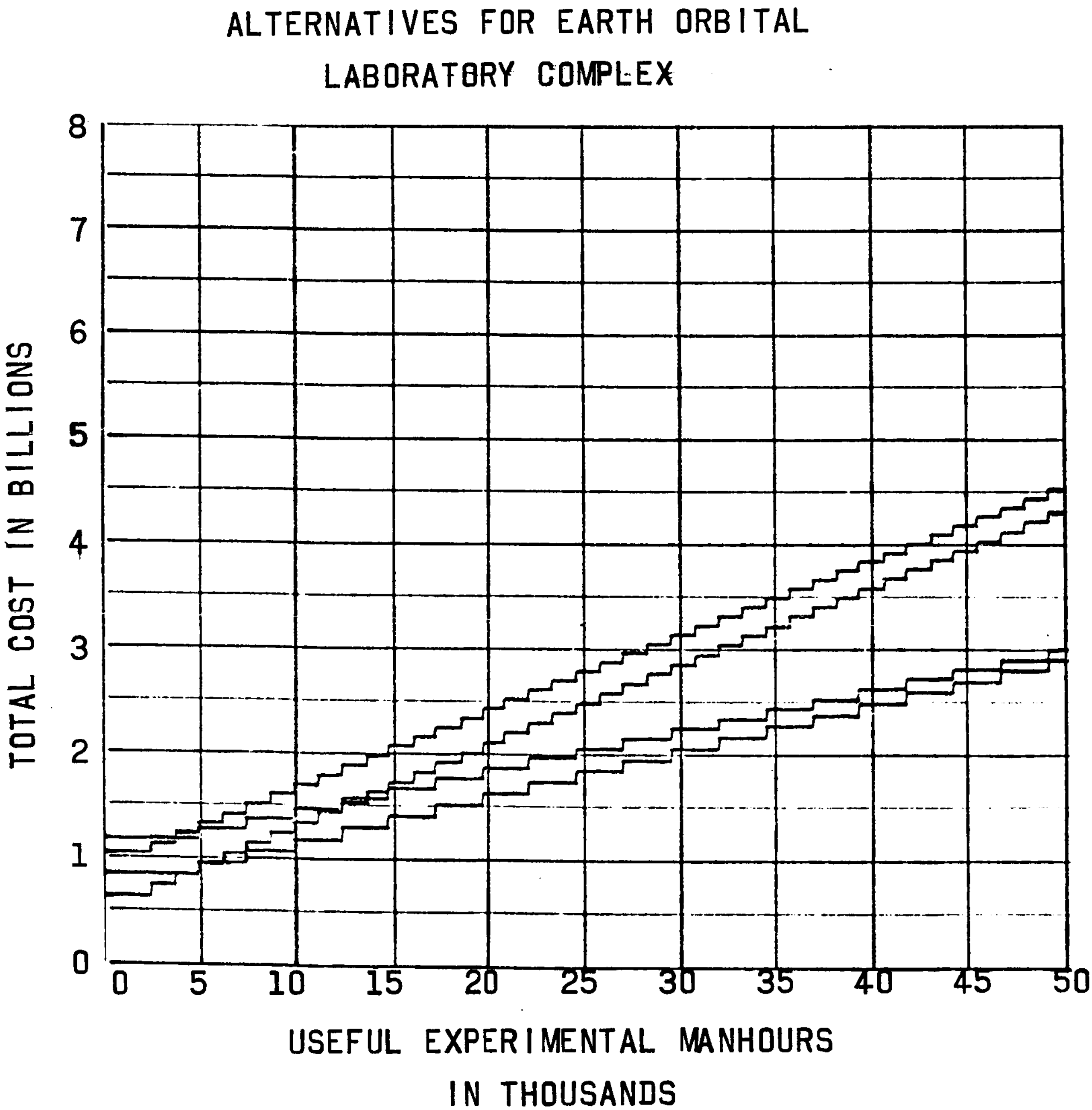
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Figure 3

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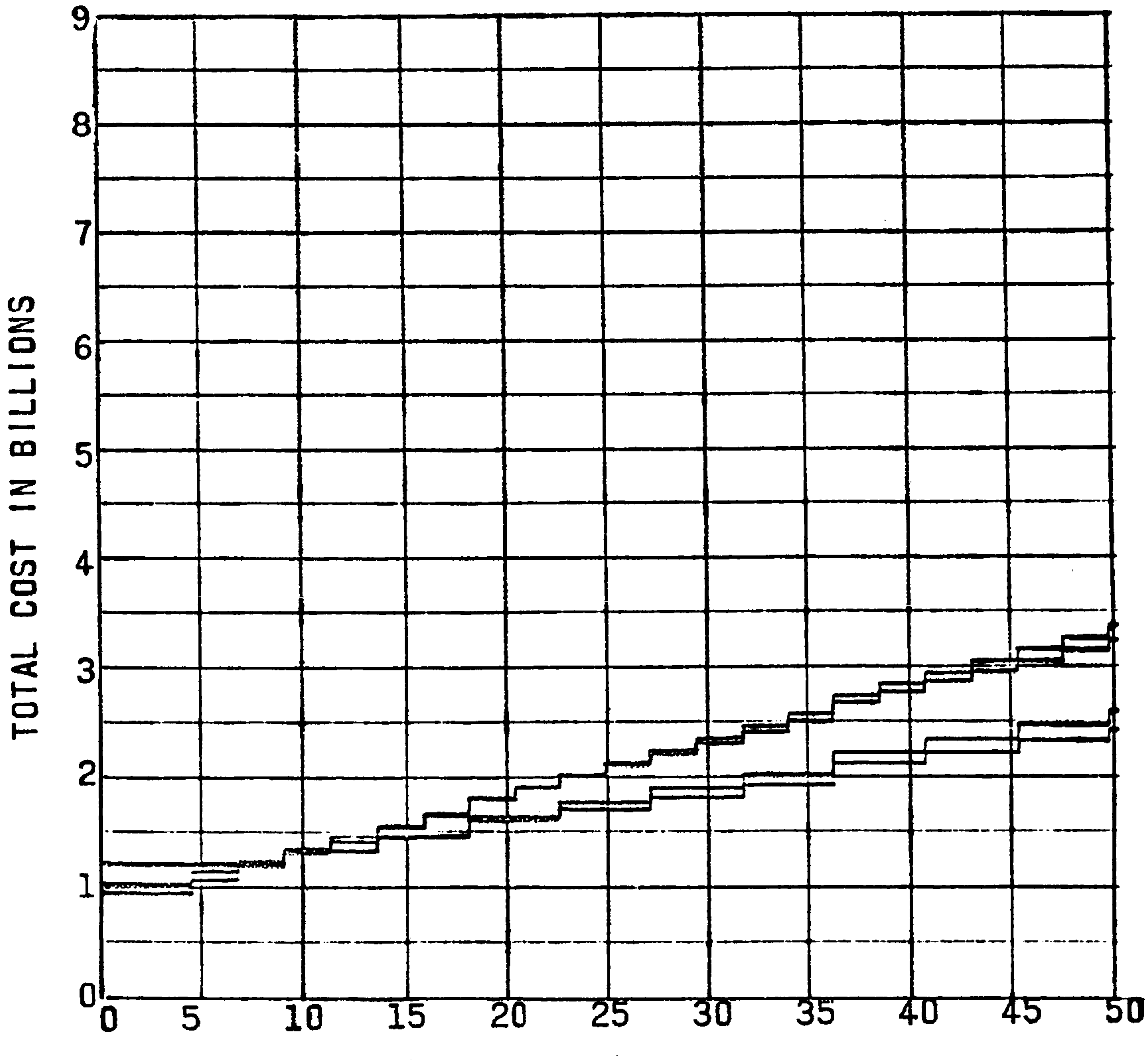

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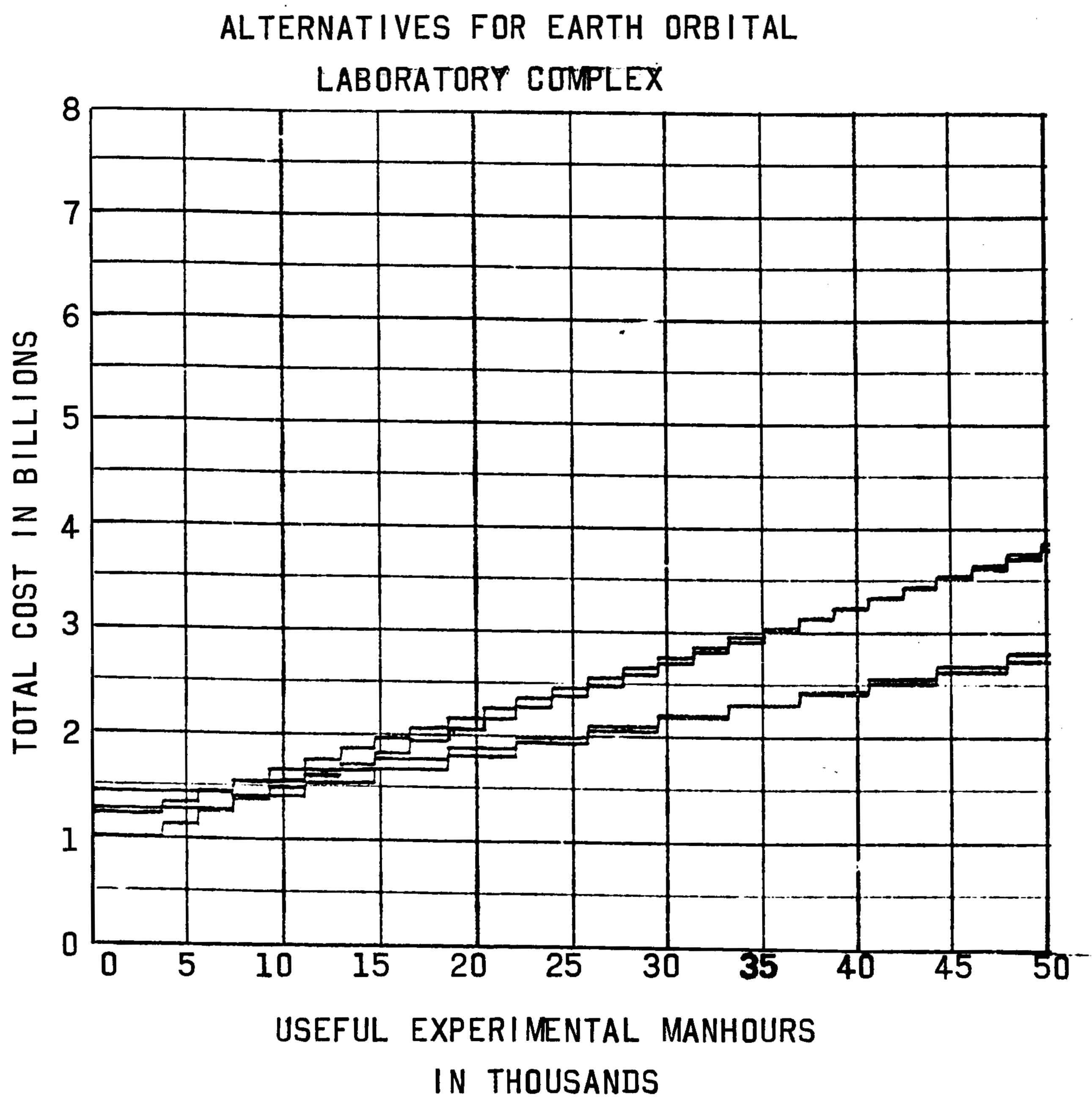
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Figure 5

ALTERNATIVES FOR EARTH ORBITAL LABORATORY COMPLEX

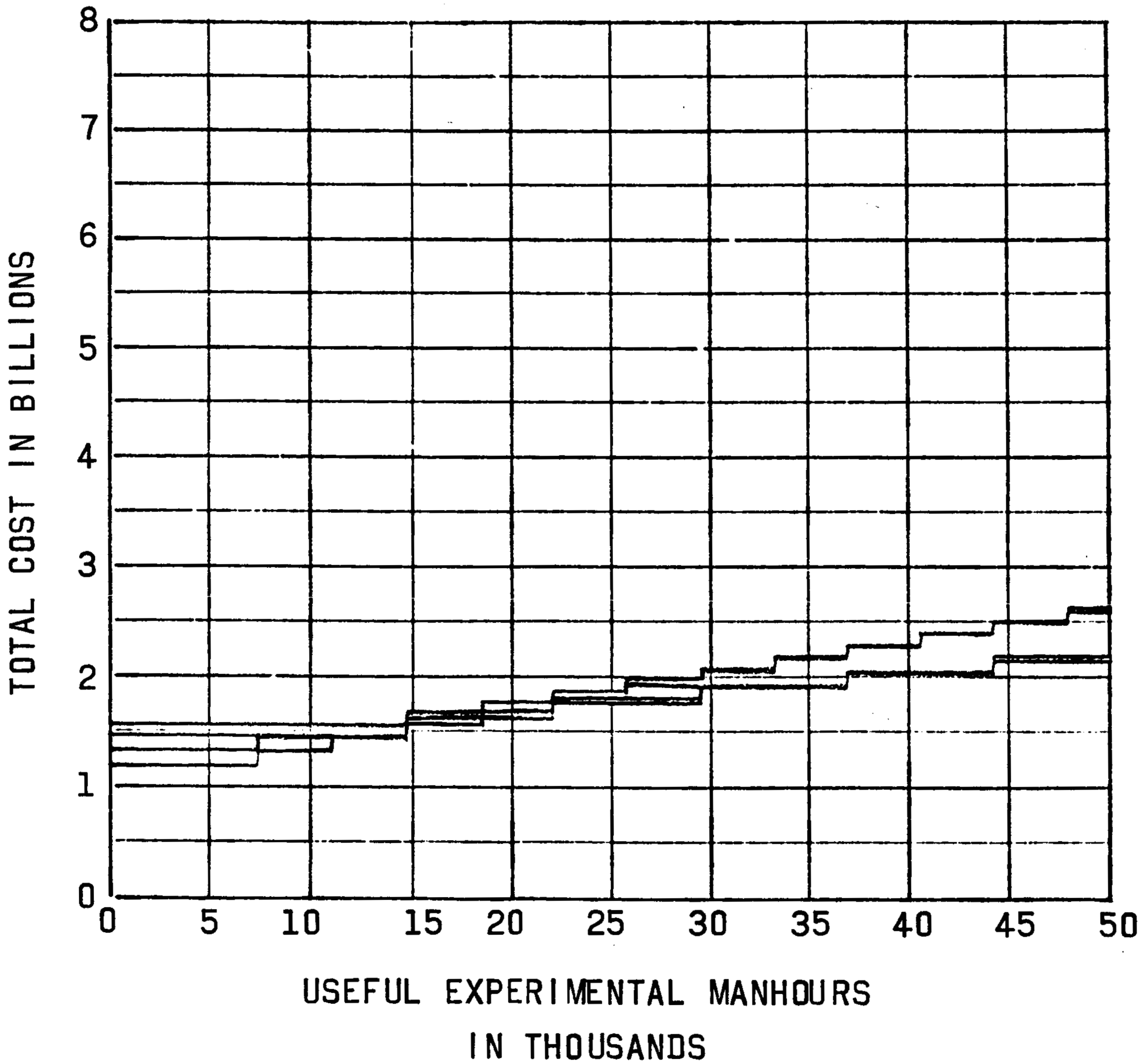
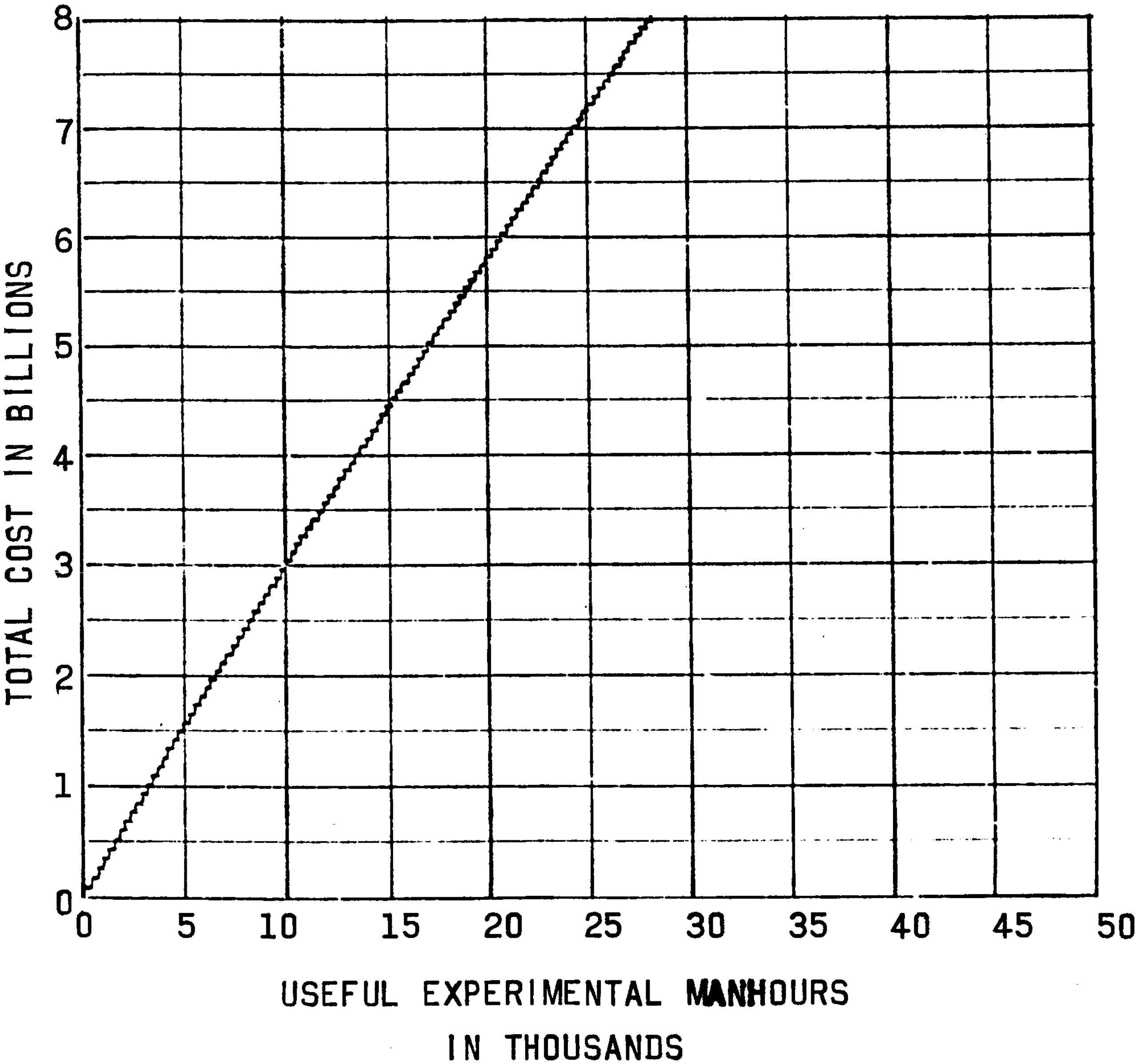


Figure 6

ALTERNATIVES FOR EARTH ORBITAL
LABORATORY COMPLEX



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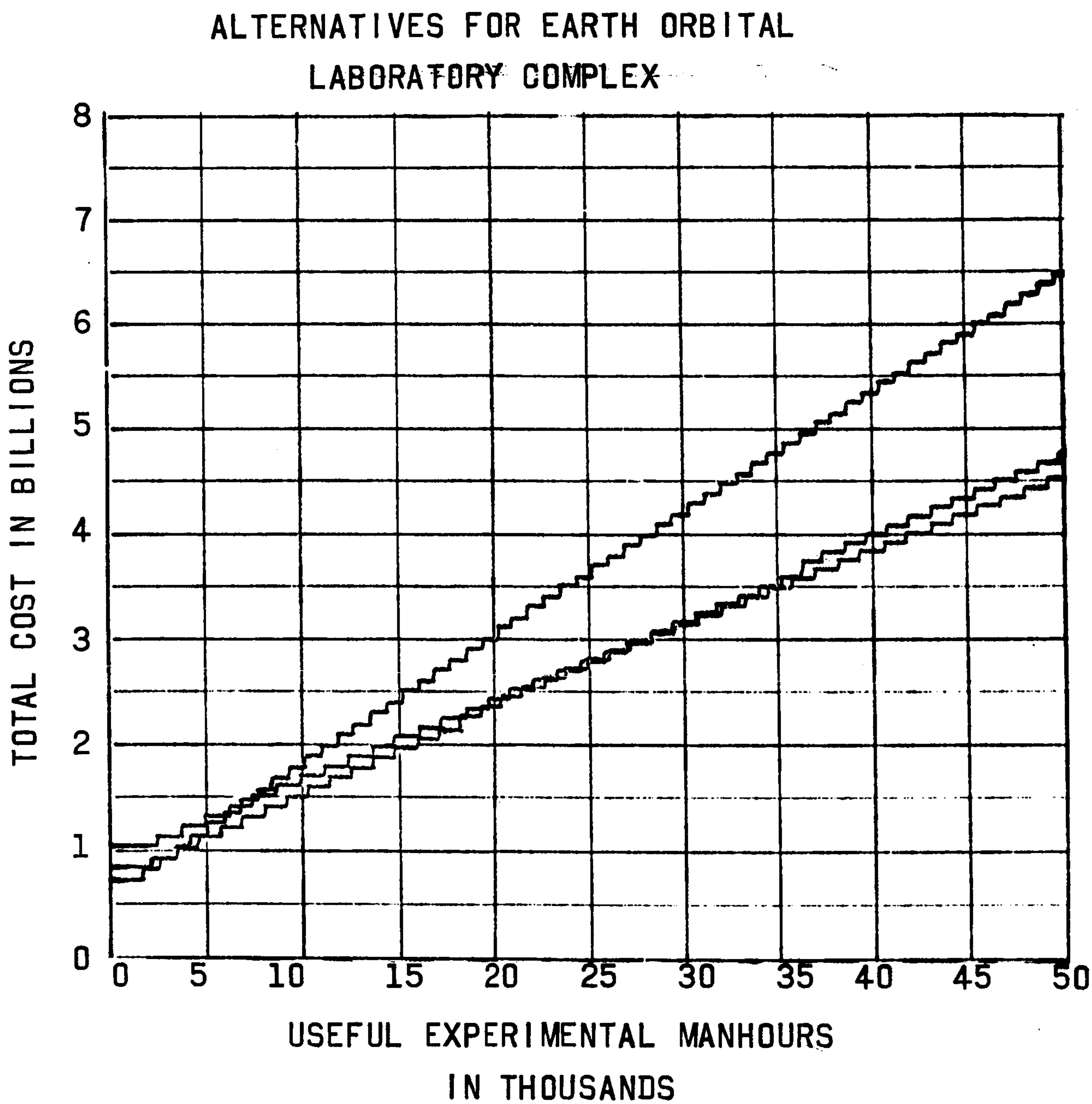
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Figure 8

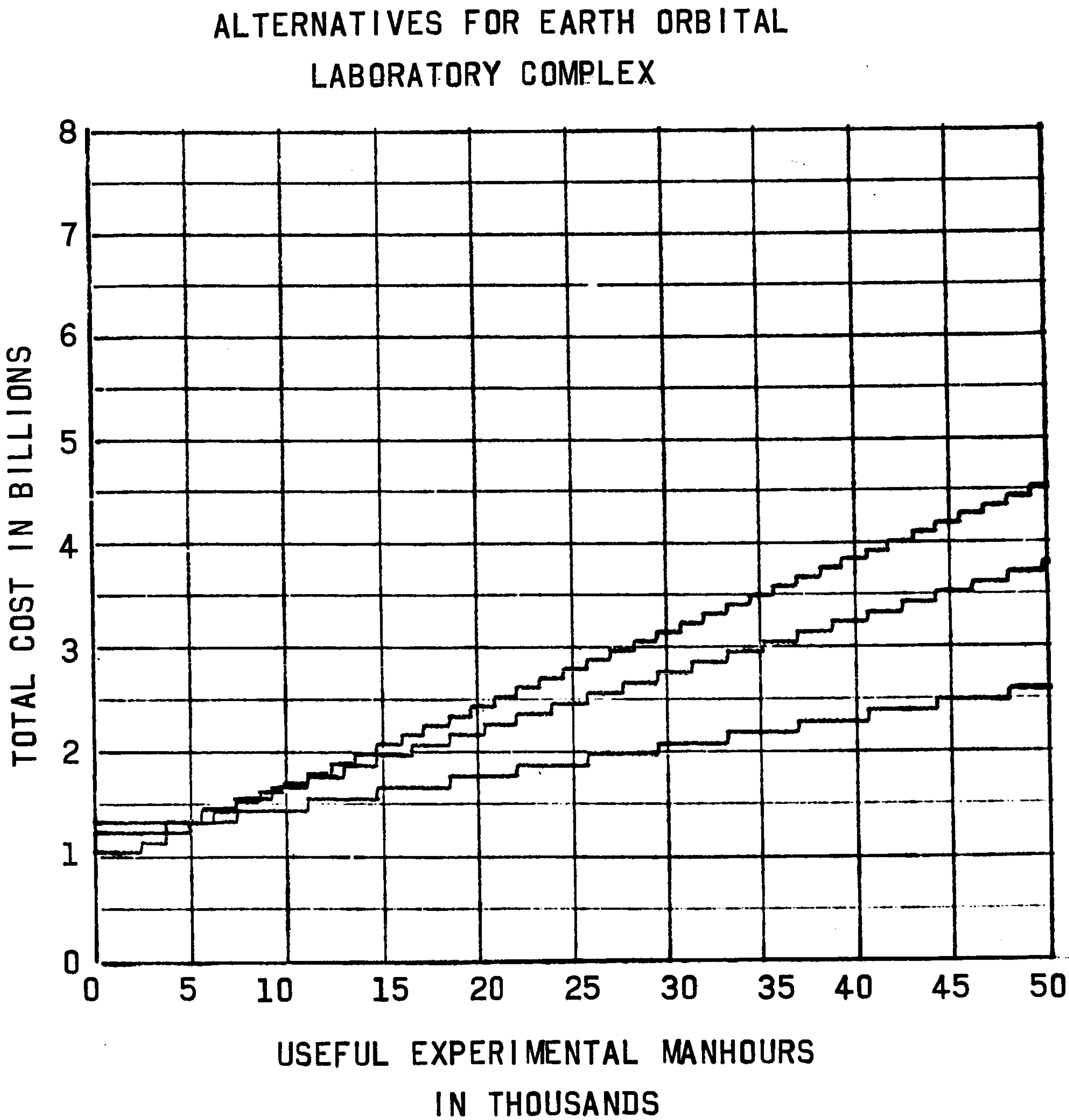
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Figure 9

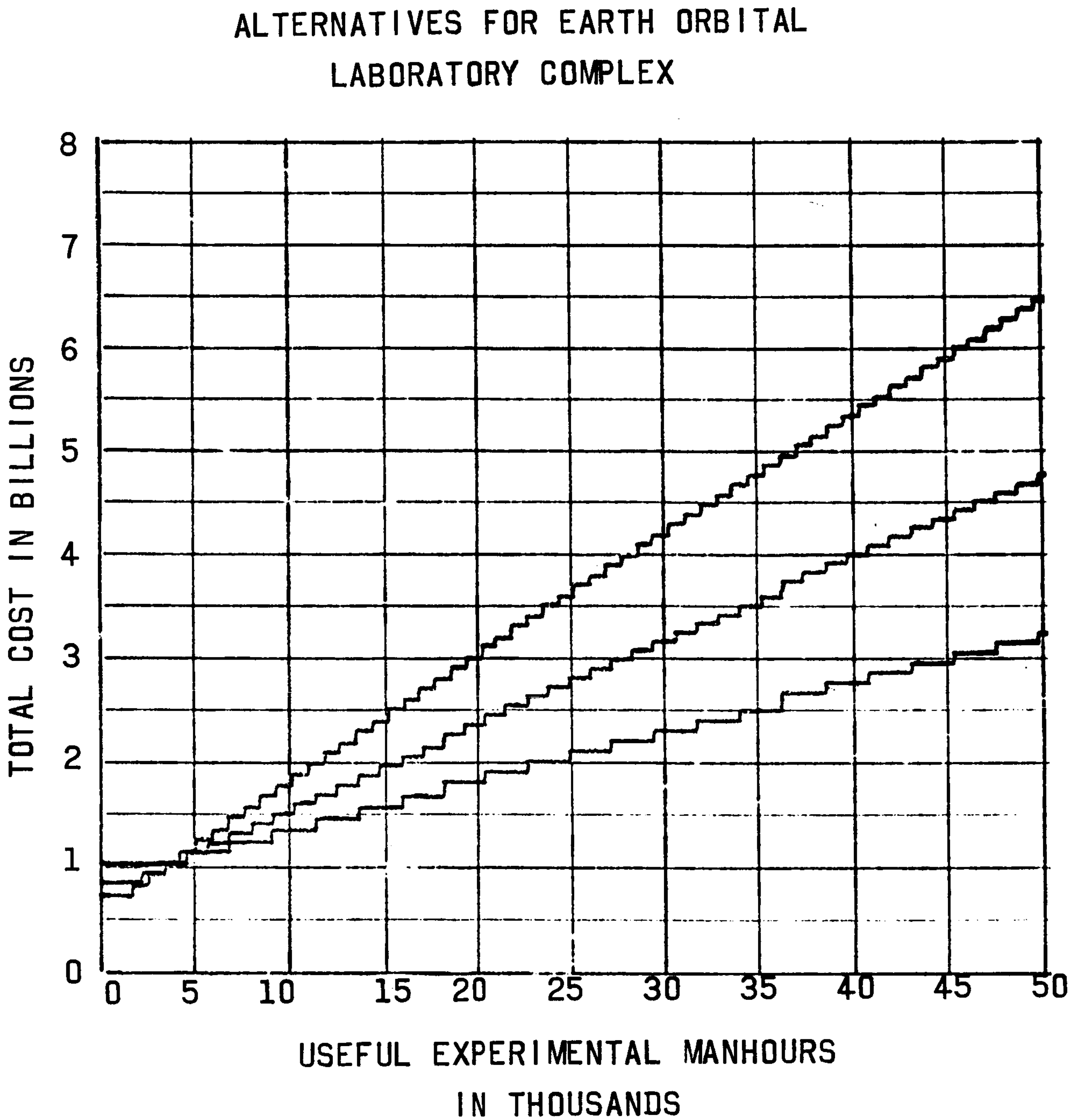

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Figure 10

ALTERNATIVES FOR EARTH ORBITAL
LABORATORY COMPLEX

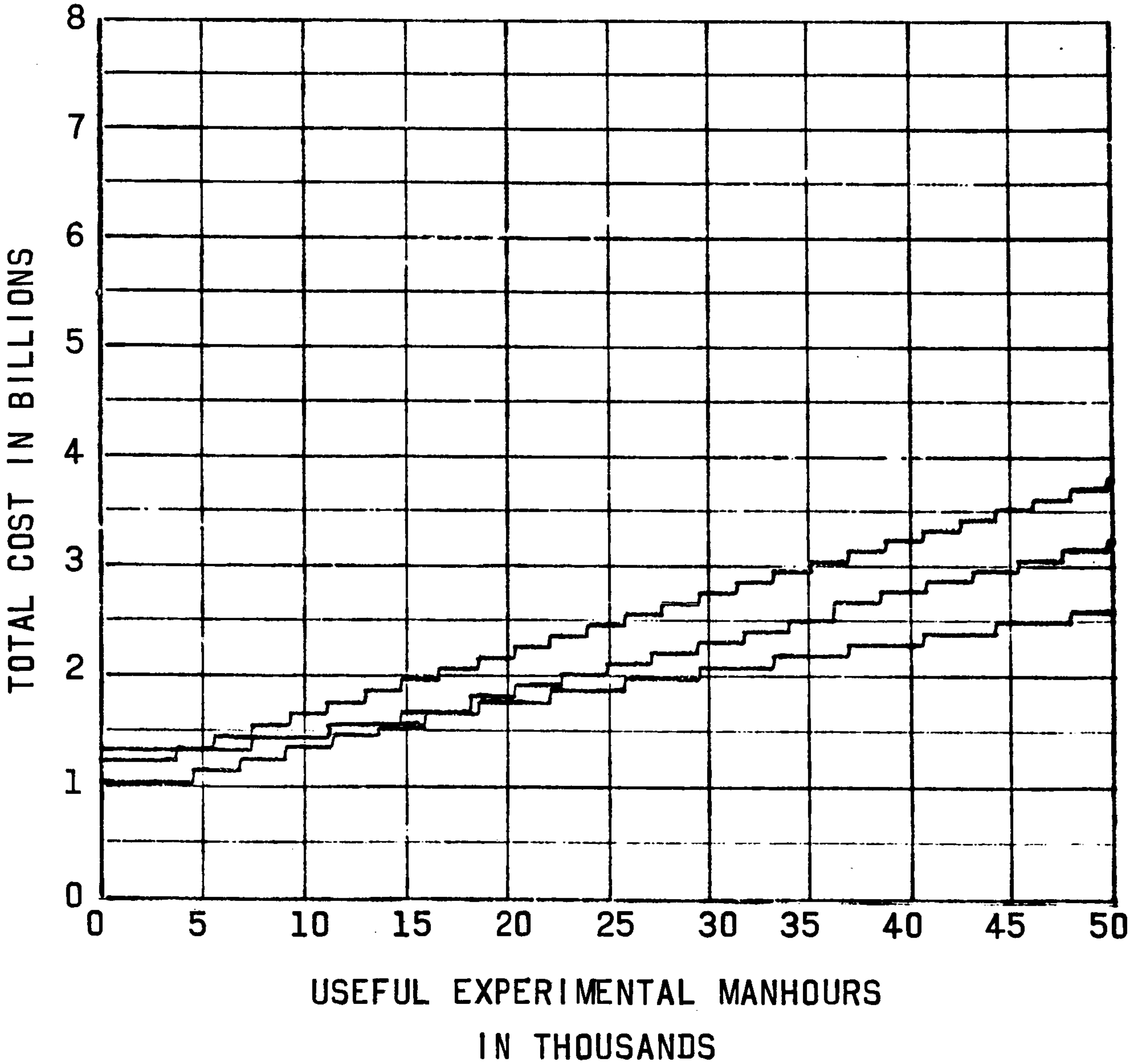

Figure 11

TOTAL COSTS FOR ALTERNATIVE CONCEPTS

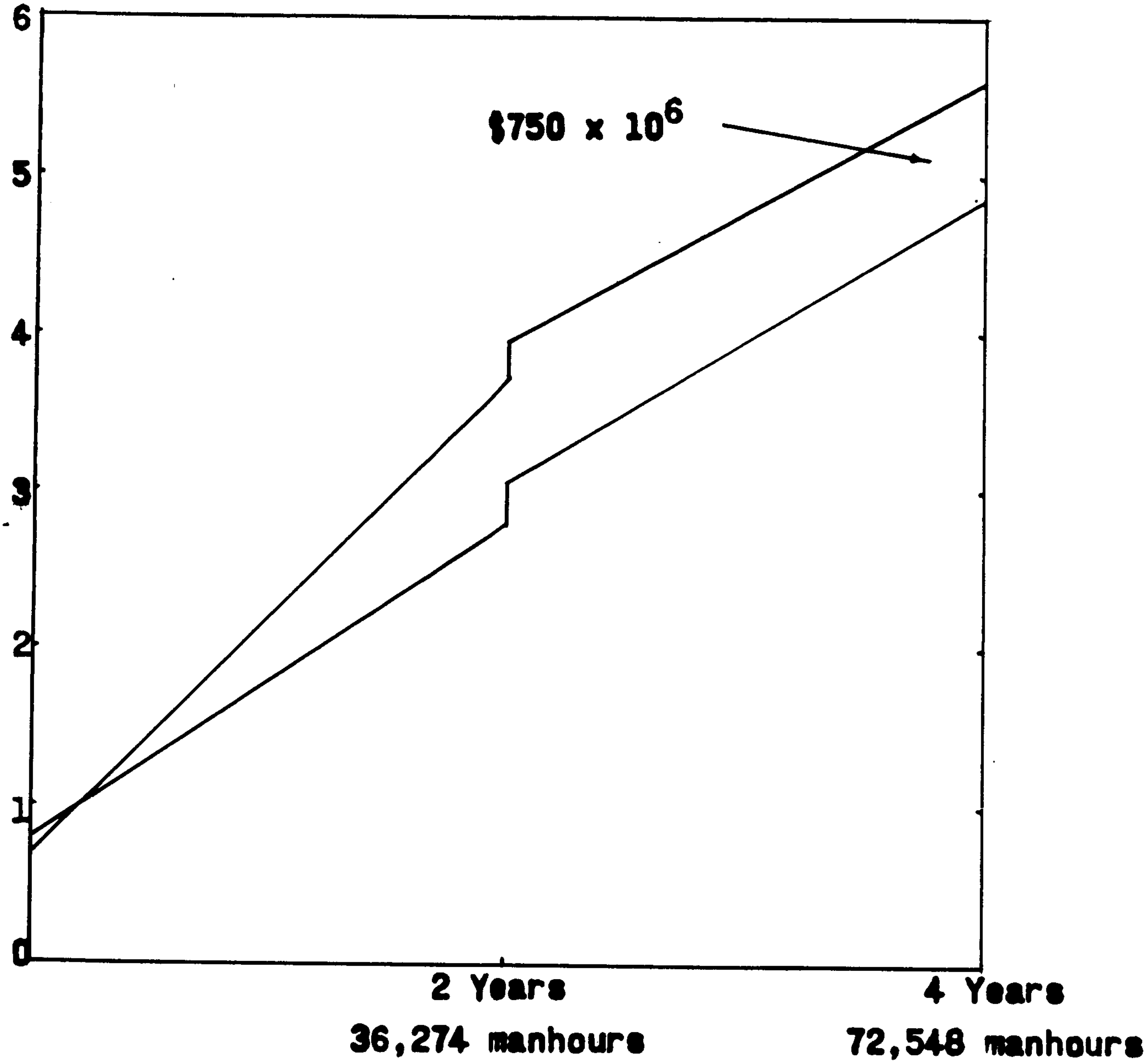

Figure 12